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A Review of the Methods of Economic Analysis of Nuclear Power Plants

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A Review of the Methods of Economic Analysis of Nuclear Power Plants

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Report

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Abstract

A Review of the Methods of Economic Analysis of Nuclear Power Plants

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Nuclear power plants across the United States are reaching the end of their current operating licenses, forcing decision makers to think about the way forward. As they consider the best alternatives for dealing with aging nuclear plants, it is becoming increasingly important to have an accurate method for calculating the long-term costs of nuclear power plants. This report begins by investigating the methodologies currently used in these calculations. They focus on the uncertainty associated with deregulated electricity markets and can be broken down into two main categories: discounted cash flow and real options analysis. Next the report discusses the limitations of the current methodologies, focusing specifically on those aspects of evaluation that are currently eclipsed by electricity market uncertainty. Finally the report offers recommendations for addressing these limitations and creating a stronger analytical framework for calculating the lifetime cost of nuclear power plants.

Table of Contents

List of Figures

1. Introduction

There are currently one-hundred and four commercial nuclear reactors operating in the United States. Combined they supply approximately twenty percent of the nation's electricity, making the United States the largest provider of commercial nuclear power in the world (World Nuclear Association, 2011). Despite the nation's preeminence in the nuclear energy industry, construction on all of the country's reactors began prior to 1974 (Wald, 2010). Thus the average age of nuclear power plants in the United States is thirty years old; meaning many of the nation's nuclear power plants will soon be reaching the end of their licensed life. In the United States, nuclear power plants are originally licensed for forty years, a figure based on the accounting practices that were standard at the time of its inception. Currently, the U.S. Nuclear Regulatory Commission has programs in place that allow for the extension of operating licenses in twenty year increments. The ability to extend a plant's operating license gives management one option for addressing the issue of an aging nuclear fleet, which has led to a renewed dialogue about the future of nuclear energy and what many are calling the "nuclear renaissance."

In addition to the implications of an aging nuclear fleet, the push for "clean energy" is giving nuclear power leverage in the political arena. In 2002 the Nuclear Power 2010 program was initiated by the Department of Energy (DOE) (World Nuclear Association, 2011). The program was designed to address the need for new nuclear power plants. The premise of the program was to create industry/government cost-sharing initiatives to identify sites, develop new technologies, and test new regulations for nuclear power plants. Then in 2005 the Energy Policy Act was passed, offering a number of incentives for new nuclear power plants. These incentives include extension of the Price-Anderson Nuclear Industries Indemnity Act, up to $2 billion in cost-overrun support for six new nuclear power plants, loan guarantees, and tax credits (World Nuclear Association, 2011). Additionally, President Obama emphasized the importance of nuclear energy in his 2010 State of the Union address when he said "… to create more of these clean energy jobs, we need more production, more efficiency, more incentives. That means building a new generation of safe, clean nuclear power plants in this country (Obama, 2011)." In February 2010, President Obama announced loan guarantees for two new nuclear reactors at a plant in Georgia, the first begun in the United States since the 1970's (Wald, 2010). Additionally, as of November 2010, the Nuclear Regulatory Commission (NRC) had extended the operating licenses of 60 nuclear power plants and received applications for the construction of 28 new power reactors (World Nuclear Association, 2011), (Nuclear Regulatory Commission, 2010).

The increasing number of nuclear power plants reaching their planned operating life combined with the political momentum surrounding nuclear energy has opened the door for the "nuclear renaissance," forcing the nuclear community to address tough decisions about their future. In order to make these difficult decisions, it is critical for the nuclear power industry to take a serious look at the feasibility of plant lifetime extensions and to consider the prospect of building new plants to replace the aging fleet. One of the fundamental steps for addressing these issues is the performance of comprehensive economic analysis. The long life, uncertainty, and high capital costs associated with nuclear power plants make this analysis complicated. In order to accurately estimate the lifetime cost of a nuclear power plant, many factors must be taken into account. Among these factors are time-discounting, time-dependency of capacity and efficiency factors, and market risk.

The current methods used to calculate the lifetime cost of nuclear power plants can be divided into two main categories: discounted cash flow and real options analysis. Although the current methodologies provide users with the tools necessary for sound economic analysis, they do not accurately account for all of the uncertainty present in nuclear projects. Additionally, they do not incorporate managerial flexibility or the effects aging have on plant costs and operations. These limitations combined with the lack of consistency in lifetime cost analysis leave a lot of room for improvements, such as the inclusion of the option to abort a project in economic analysis and the use of a systems approach to lifetime cost evaluation. In the following sections I am going to discuss in more detail the methodologies currently in use, their limitations, and recommendations for improvement.

2. Current Methodologies

As a plant approaches the end of its operating license, decision makers must consider the future of the plant. Regardless of whether that future includes a lifetime extension or decommissioning and construction of a new plant, it is critical for a lifetime cost analysis to be performed. There are several methodologies currently used in lifetime cost estimation. Each of these methods approach lifetime cost estimation in different ways. I am going to begin my discussion of current valuation methodologies by discussing the parameters that affect the calculations and then I will discuss the discounting methods used to account for volatility and future cash flow.

2.1 Parameters

In order to fully represent the lifetime cost of a nuclear power plant, a number of costs and parameters must be taken into account. Although these factors can vary slightly from project to project, there are four universal components that must be considered in all economic evaluations. Along with these components, a number of risks must be taken into consideration.

The first factor that must be considered when calculating the lifetime cost of a nuclear power plant is capital or construction cost. It makes up approximately 60% of the total cost associated with new plants (Kessides, 2010). Additionally, capital costs for nuclear power are extremely uncertain. This uncertainty stems from the possibility of construction delays caused by safety and regulatory issues and by the complexity of the technology used in nuclear power plants (Kessides, 2010). Uncertainty also arises from the long-term interest rates associated with the initial capital investment and their volatility. Although there are data available on the cost of nuclear power plant construction in countries such as China and India, there are little data on current construction costs in the United States. Additionally, the United States has enacted new licensing processes (i.e. Combined Licenses) which are not represented in the current data. The lack of up-to-date and accurate data makes it difficult to accurately estimate construction costs or its volatility.

Another factor that needs to be included in lifetime cost estimates is operations and maintenance costs, which make up around 20% of the total cost of new plants (Kessides, 2010). It includes administration, management, equipment replacement and upgrades, preventive maintenance, regulatory and licensing fees, back-end, and other general operating costs (Kessides, 2010). Back-end costs refer to the cost for decommissioning nuclear power plants and final waste disposal. Since few plants have undergone decommissioning, little is known about the true back-end cost. Additionally, estimates of back-end costs are plagued with uncertainty due in large part to the lack of a final repository for nuclear waste. Although these issues can be detrimental to nuclear power plant projects, they do not play a major role in lifetime cost calculations because the costs occur so far in the future that they have little effect on the net present value of the project. It should be noted however that as the cost and uncertainty associated with decommissioning grow, they can take on a more prominent role in the overall economic evaluation.

The last 20% of the total cost of new nuclear power plants is made up of fuel costs (Kessides, 2010). For nuclear power plants, fuel costs include the cost of uranium, the processing costs required to prepare the raw uranium for use, and the cost to dispose of spent fuel.

In addition to the general costs that arise in all nuclear power plants, there are a number of risks that must be considered. The passage of the 1992 Energy Policy Act led to the deregulation of the wholesale market for electricity. With electricity prices now being determined by supply and demand, nuclear power plants are no longer able to pass the risk of construction delays and cost overruns onto customers (Graber & Rothwell, 2006). Since the burden of overruns and delays now fall on the investor, it is critical to accurately portray the risk involved in construction. Another product of deregulation is the need to account for volatility in the electricity market. Lifetime valuation methods must incorporate methods for accurately estimating and accounting for uncertainty in the electricity market. Finally, risks in the cost and production of fuel need to be included in economic analysis. Although the fuel market for nuclear power is less volatile than the markets for oil and gas, it still plays a role in the net present value calculation. In addition to these risks, each project may have additional risks that are unique to the project.

2.2 Discounting

Due to the nature of nuclear power plants, their extended construction period, high capital cost, and long lives, the discounting method used for the analysis is vital. There are a number of different methods for discounting cost and accounting for uncertainty. The two predominant methods discussed in the literature were discounted cash flow and real options analysis.

2.2.1 Discounted Cash Flow

Discounted cash flow analysis is a method of valuing assets, which discounts projected future cash flows to calculate the present value of an asset. One of the driving principles behind the discounted cash flow approach is that the money received today is more valuable than money received in the future. As such, the timing of cash flows and the discount rate employed are critical (Ramana, D'Sa, & Reddy, 2005). Additionally, the cost of the asset is extremely sensitive to the chosen discount rate. Thus the critical component of discounted cash flow is determining the appropriate discount rate. The discount rate accounts for the time-value of money, which is represented by the risk-free rate, and the risk premium. A simple example of a discounted cash flow calculation is given in Example 1 below.

Example 1: Consider a nuclear power plant that could be built in 1 year for a cost of $200 million. After construction is completed, the plant will operate for five years. During those five years, the price of electricity will be $0.05 per kWh and the plant will produce 1300 kWh annually. For a discount rate of 10%, the NPV can be calculated as follows (in millions of US $):

$$NPV = \sum_{t=0}^{t=5} \frac{R_t - C_t}{(1+r)^t} \tag{1}$$

$$= -200 + \frac{65}{(1.1)^1} + \frac{65}{1.1^2} + \frac{65}{1.1^3} + \frac{65}{1.1^4} + \frac{65}{1.1^5}$$

$$= 46.4$$

where

R_t*: the revenue in year t.*

C_t*: the cost in year t.*

r *: the discount rate.*

Since the net present value is positive (NPV>0) in this example, it would be economical to build and operate this plant for the given costs, revenues, and discount rate. Thus, if the decision being considered is a simply whether or not to build the plant, the above results indicate that the plant should be built.

There are a number of approaches for determining the appropriate discount rate. One method for determining an appropriate discount rate is the use of the capital asset pricing model (CAPM), which is frequently used in finance to calculate an appropriate required rate of return. The CAPM, which is given in Equation 2 below, establishes a relationship between the asset's sensitivity to non-diversifiable risk, the expected market return, and the risk-free rate of return.

$$E(R) = R_F + \beta * [E(R_m) - R_F] \tag{2}$$

where

$E(R)$: the expected return on the asset.

R_F: the risk-free rate of return.

$E(R_m)$: the expected market return

$\beta = \frac{Cov(R_m, R_F)}{Var(R_m)}$: a measure of the sensitivity of the asset to non-diversifiable risk.

The CAPM method is used by Takizawa and Suzuki to determine the discount rate used in net present value calculations for comparisons to a real options approach (Takizawa & Suzuki, 2004). Another method for determining an appropriate discount rate is used in "Economics of Nuclear Power from Heavy Water Reactors" (Ramana, D'Sa, & Reddy, 2005). The authors use the ratio of Gross Domestic Product (GDP) deflators given by the World Bank to convert costs from one year to another. GDP deflators are measures of the change in price of all domestically produced goods and services in a country over a specified period of time and can be calculated by taking the ratio of nominal to real GDP. In addition to using GDP deflators to convert costs to 2002 rupees, the authors used a discount rate to convey the investors' and planners' desired resource allocation scheme and their value of future benefits compared to current costs. Since the value planners place on future benefits versus current costs is subjective, the discount factor used in the authors' analysis was not easy to determine. In order to compensate for the difficulty in assessing an appropriate discount rate, the authors calculated the net present value using several discount factors (Ramana, D'Sa, & Reddy, 2005). Finally, Takizawa *et al* used the riskless interest rate as the discount rate in their calculations.

2.2.2 Real Options

Real options analysis uses the technique of options valuation for capital budgeting. In particular, the real options approach to valuation allows for the consideration of management flexibility in decision making. Additionally, real options use a different approach for dealing with uncertainty. Unlike traditional net present value analysis, which assumes that all uncertainty is reflected in the risk premium, real options evaluate uncertainty individually for each cash flow (Rothwell, 2006). Once uncertainty has been assessed, the risk-free rate is used to discount the cash flows in each year. In the absence of management flexibility, the only difference between discounted cash flow and real options is their approaches to dealing with uncertainty. The real options approach uses a time-varying discount rate while discounted cash flow use a constant rate (Samis, Davis, Laughton, & Poulin, 2006). An example of Real Options valuation will be demonstrated in Example 2 below.

Example 2: Consider a nuclear power plant that could be built in 1 year for a cost of $200 million. After construction is completed, the plant will operate for five years. During the first year of operation, the price of electricity is assumed to be $0.05 per kWh. During the remainder of the plants lifetime, the price of electricity will increase by $0.01 with a probability of 50% and will decrease by $0.01 with a probability of 50%. Each year the plant will produce 1300 kWh of electricity. The risk-free rate is assumed to be 3%.

Using the base electricity price and the probability of the price increasing or decreasing by $0.01, we are able to create the binomial event tree depicted in Figure 1. Once the electricity price at each time step is calculated, we can input the prices into Equation 3 to calculate the Expected Net Present Value (ENPV) at each time step. The event tree depicting the ENPV of the plant can be seen in Figure 2.

$$ENPV_t = \frac{R_t - C_t}{(1+r)^t} + .5 * \left(\frac{R_{t+1,+0.01} - C_{t+1,+0.01}}{(1+r)^{t+1}}\right) + .5 * \left(\frac{R_{t+1,-0.01} - C_{t+1,-0.01}}{(1+r)^{t+1}}\right) \tag{3}$$

where

R_t: the revenue in year t, which is the price of electricity in year t multiplied by the amount of electricity produced in year t.

C_t: the cost in year t, which in this example is zero in every year expect t = 0.

r : the discount rate.

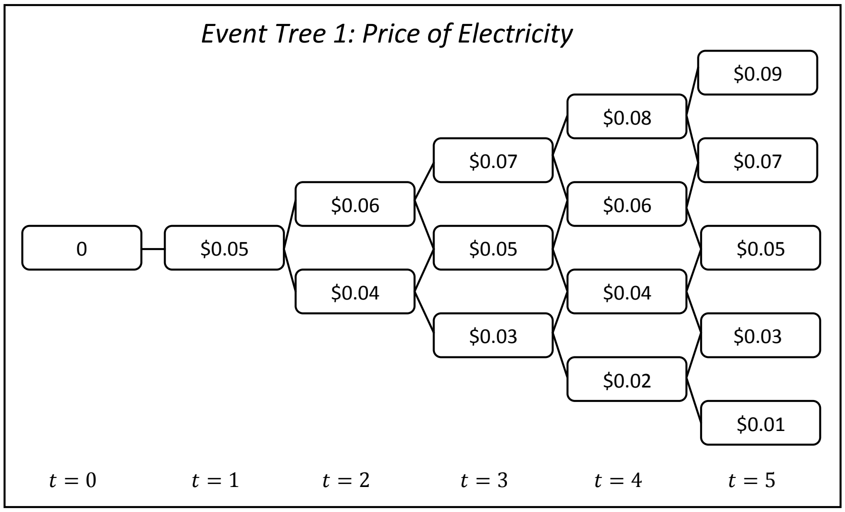

Figure 1: Event Tree for Price of Electricity used in Example 2

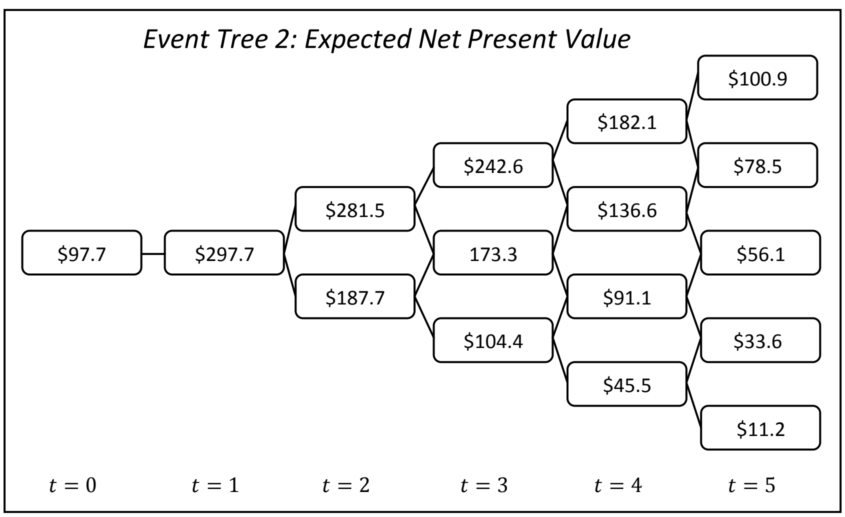

Figure 2: Event Tree for net Present Value Results obtained from Example 2

Since the expected net present value is positive (ENPV >0), decision makers would be advised to build the plant. One should note that the ENPV in year one is called the value of the option to construct a new nuclear power plant, where as the ENPV in year zero is the difference between the value of the option to construct a new power plant and the cost of exercising that option, which in this case was $200 million. Thus, another rule for deciding whether or not to build the new plant is to build if the value of the option to construct the new plant ($297.7) is greater than the exercise price of the option ($200.0). In this example, the results indicate that the new power plant should be built.

Japan: Deregulated Electricity Market

In 1995 Japan's Electric Utility Industry Law was amended to open the generation and wholesale supply markets to independent power producers. It was the first step in the deregulation of Japan's electricity market (Takahashi, 2002). With plants forced to operate in a new environment, a number of economic studies were performed to evaluate the costs of nuclear power in a deregulated market.

In 2001 Takizawa *et al* examined the use of real options to evaluate the investment for construction of a nuclear power plant. In their model, the authors considered the uncertainty in both the electricity market and the uranium fuel market. The prices of both electricity and uranium are assumed to follow Geometric Brownian Motion (GBM), which is a continuous time stochastic process frequently used in pricing models. GBM is most commonly known for its use in the Black-Scholes model. Its popularity stems from its ease of use and its ability to accurately capture the volatility seen in real markets, such as the stock market. Additionally, the authors assume that the prices of uranium and electricity are positively correlated with one another. Using these assumptions a method for calculating the critical price of electricity, which is the price at which the investment in the nuclear power plant will be justified, is created. The critical price of electricity is the electricity price that satisfies the following equations:

$$H(P) = V(P) - Q \qquad (4)$$

$$H'(P) = V'(P) \qquad (5)$$

where

$H(P)$: simplified version of $H(P, F)$, which is the value of the option to invest in the NPP as a function of the electricity price, P, and the uranium price, F. The simplification of $H(P, F)$ to $H(P)$ is made possible by the assumption that P and F are positively correlated with one another.

$V(P)$: the project value as a function of the electricity price P.

Q: the cost of construction.

$H'(P)$: the derivative of $H(P)$ with respect to P.

$V'(P)$: the derivative of $V(P)$ with respect to P (Takizawa, Omori, Suzuki, & Ono, 2001).

If the current average market price of electricity, P, is greater than the critical price of electricity, P^*, then the option to invest in the NPP should be exercised (Takizawa, Omori, Suzuki, & Ono, 2001). The authors used their model on a reference case and were able to show that the critical price of electricity calculated using real options valuation was significantly higher than the price calculated using the standard net present value approach. This implies that the real options approach provides a more rigorous test of a project's profitability over its lifetime than the standard net present value approach. The authors also discovered that as the amount of volatility in the market prices of electricity and uranium increase, so does the critical price of electricity (Takizawa, Omori, Suzuki, & Ono, 2001). From this result, it is clear that as volatility increases, the likelihood of a project being profitable over its lifetime decreases. In other words, increased uncertainty in the price of electricity and uranium decreases the value of the project.

Takashima *et al* also examined the use of real options to represent the uncertainty inherent in a deregulated market. The authors considered the option of decommissioning the nuclear power plant and the option of replacing the plant's equipment. Like Takizawa *et al*, they used GBM to represent the price of electricity. They did not, however, consider uncertainty in the price of uranium (Takashima, Naito, Kimura, & Madarame, 2007). For further information about the price of uranium, refer to Appendix A: Uranium Prices. Takashima *et al* also assume variable costs are constant because they are less volatile than electricity prices. Their model allows users to calculate the value of the nuclear power plant and the threshold electricity prices for replacement and decommissioning. Using their model, the authors were able to determine the optimal rule for decommissioning and replacement. This optimal decision is to decommission the plant if the price of electricity falls below the threshold price for decommissioning and replace the plant's equipment if the price of electricity rises above the threshold price for replacement. If the price of electricity falls between the two threshold prices, neither option is exercised (Takashima, Naito, Kimura, & Madarame, 2007). One should note that the cost of equipment replacement is assumed to be constant and the capacity factor of the plant is assumed to be the same before and after replacement. In addition to discussing a real options model for decommissioning and replacement, Takashima *et al* used Monte Carlo simulation to calculate the probability that each option is exercised and its expected exercise time. Using these data, the authors were able to conclude that when considered in tandem with the option to replace plant equipment, the threshold price for decommissioning is lower than when the option of replacement is not considered, which implies that decision makers should be more hesitant to decommission an active plant if they have the option to replace faulty or outdated equipment in the future. Additionally, Takishima *et al* found that increased market volatility leads to an increased probability of postponement of the decision to decommission or replace plant equipment, thus extending the expected time of replacement (Takashima, Naito, Kimura, & Madarame, 2007). These results imply that increased uncertainty in electricity market prices should cause decision makers to postpone their decision until more information is available, which seems logical since uncertainty in electricity prices lead to a decrease in the threshold price of decommissioning and an increase in the threshold price of replacement (Takashima, Naito, Kimura, & Madarame, 2007).

Naito *et al* discuss the decision to replace a nuclear power plant on the same location as a currently operational plant. Using real options and time lags, the authors determine the optimal time to decommission the current plant and begin construction on the new plant. In their paper, the authors consider two options: a decommissioning options and a combined decommissioning and replacement option. In the combined option case, time-lags are used to examine the effect of decommissioning time on the value of the option. Additionally, the cost and duration of construction is considered fixed and fuel costs are assumed to be proportional to the capacity factor, which is different for the plant currently in operation and the replacement plant. Like the analysis presented in the previous two papers, the real options model is used to calculate a critical or threshold price of electricity. Naito *et al* were able to conclude that the value of the combined option was greater than the value of the decommissioning option alone (Naito, Takashima, Kimura, & Madarme, 2010). This result is consistent with Takashima *et al*'s results and emphasizes the importance of considering all of the options available to management when trying to accurately estimate lifetime value (Takashima, Naito, Kimura, & Madarame, 2007).

The deregulation of Japan's electricity industry prompted the study of real options as a means of incorporating market uncertainty into cost estimation and decision making. Using GBM as a model for the electricity market, the authors discussed above were able to consider the economic viability of the decommissioning, construction, and equipment replacement of nuclear power plants. The critical factors of the methods used in the preceding papers are the technique for accounting for uncertainty and the consideration of multiple sequential options in plant valuation. Both of these techniques allow the decision maker to better understand the uncertainty facing them and the alternatives that are open to them.

Estimating Electricity Prices: Enhancements and Modifications

In Japan, the uncertainty associated with a deregulated electricity market is predominantly modeled using standard GBM. Although standard GBM is commonly used to model volatility in market prices, there are a number of modifications that can be incorporated into GBM to make it more realistic. Among the enhancements that can be considered are the use of futures markets to aid in parameter estimation and mean reversion, which is the tendency for a stochastic process to return to the long-run average value over time (Abadie, 2009).

Abadie *et al* added an additional layer to standard GBM by incorporating their knowledge of the futures market on energy commodities. According to Abadie, "By using the futures markets [on energy commodities] we have avoided the need to know future cash flows, which are uncertain, and also the need to compute a suitable risk premium (Abadie, 2009)." This point is reinforced by Samis *et* al in "Valuing uncertain asset cash flows when there are no options: A Real Options Approach." According to them "The advantage [here] is that there is no need for any calculation of risk discount rates – they are imbedded in the forward price." Once data have been collected on the futures prices, they are used to calculate the expected spot price of the energy commodity in a risk-neutral world. The value of the expected spot price can then be used to estimate the parameters associated with GBM and thus model the behavior of the futures market in the distant future (Abadie, 2009).

Abadie *et al* also consider the use of mean reversion in their model of electricity prices. Rather than using standard GBM to model electricity prices, they use the more general Inhomogeneous Geometric Brownian Motion (IGBM), which is includes GBM as a special case. The model for IGBM follows below:

$$dS_t = k(S_m - S_t)dt + \sigma S_t dW_t \tag{6}$$

where :

S_t: the price of the underlying commodity at time t.

S_m: the level to which the commodity price tends in the long run.

k: the speed of reversion towards S_m.

σ: the instantaneous volatility of the commodity price.

dW_t: the increment to a standard Wiener process, which is a continuous time stochastic process with stationary independent increments (Abadie, 2009).

IGBM incorporates reversion to the mean by setting $S_m$to the appropriate parameter. In the case of GBM, S_m is equal to zero. In Abadie *et al's* opinion, "Failure to consider this behavior [mean reversion] can lead us to undervaluing long-term investments, such as those in energy assets with decades-long useful lives (Abadie, 2009)." Hamm and Borison agree with the view that mean reversion is important when forecasting electricity prices. Hamm and Borison note that although there is a strong logical argument for the use of mean reversion, there is not strong statistical evidence supporting the need for mean reversion in the modeling of electricity prices (Hamm & Borison, 2006). Despite the lack of statistical evidence, mean reversion provides another layer of modeling that can be employed to more accurately represent the electricity market. In my opinion, additional research is needed into mean reversion in the electricity pricing market since its incorporation could help to provide a better understanding of the underlying behavior of the market and the best methods for capturing that behavior.

Accounting for Uncertainty in Other Areas

The deregulation of electricity markets around the globe has shifted the focus of lifetime valuation of nuclear power plants to methods for dealing with uncertainty in the electricity market. Although deregulated market pricing plays an important role in nuclear power plant valuation, it is not the only source of uncertainty that must be considered. Uncertainty also arises in construction cost and duration, fuel cost, and the plant capacity factor.

One method for dealing with the risks associated with variable costs, capacity factors, and construction appears in "A Real Options Approach to Evaluating New Nuclear Power Plants." Rothwell uses public data to estimate construction cost, electrical energy (MWh) generated, and operating costs for an advanced boiling water reactor. Rothwell assumes that construction costs are fixed and uses the available data to calculate a point estimate of these costs. However, rather than assuming a constant capacity factor or variable cost, Rothwell tied these parameters to time. Using ordinary least squares analysis (OLS), Rothwell was able to account for the variability associated with the capacity factor and operating costs. The OLS method allowed Rothwell to use the available data to determine appropriate functions to represent these parameters. The data showed a drastic increase in the capacity factors of operating plants throughout the 1980's and 1990's. Using the OLS method the author to was able to include these increases in the cost model. He was also able to ensure that changes in the variable cost over time could be incorporated into the model. Once suitable estimates for each of the parameters were established, the author was able to simulate the net revenue of the nuclear power plant (Rothwell, 2006).

There are a number of other ways to account for uncertainty in construction and variable costs. The authors of "Valuation and Optionality of Large Energy Industry Capital Investments" modeled the capital cost of a nuclear power plant using a lognormal distribution with a standard deviation defined by supplier contingency, which is identified in the course of meeting with suppliers. Once models for all of the uncertain parameters are determined, simulation is used to estimate a distribution for the net present value (Graber & Rothwell, 2006). The use of simulation is similar to the method used by Rothwell to determine the overall net present value of a new nuclear power plant in "A Real Options Approach to Evaluating New Nuclear Power Plants." Takizawa and Suzuki used a stochastic process to represent the variable costs associated with nuclear power. Specifically the authors use Cortazar's model, which model's the price of fuel using a stochastic process and then links it proportionally to the price of electricity (Takizawa & Suzuki, 2004). Since the fuel price follows a stochastic process, the electricity price must satisfy the following equations:

$$X = (1 - \lambda)P \tag{7}$$

$$dP = (\mu_P - \delta_P)Pdt + \sigma_P P dz_P \tag{8}$$

where :

X: the fuel cost.

P: price of electricity.

δ_P: the dividend rate of the electricity price.

μ_P: the mean electricity price.

σ_P: the volatility of the electricity price.

dz_P: the increment to a Wiener process.

As evident in the equations above, Cortazar's model for electricity prices is nothing more than a special case of IGBM with an additional proportionality constraint to link the electricity price to the stochastic process used to model fuel costs. Finally, in "Probabilistic analysis of electrical energy costs comparing: production cost for gas, coal, and nuclear power plants," the author develops a probability distribution to represent each of the cost uncertainties. These probability distributions are given in Figure 3. Once they have determined the appropriate distribution, the authors use Monte Carlo simulation to generate the probability distribution of the levelized cost of electricity. In their example, the authors use a combination of uniform (flat), triangular, and five-point distributions to represent the variable operations and maintenance costs, fuel costs, and the capacity factor (Feretic & Tomsic, 2005).

Cost	**Distribution**
Overnight Specific Investment Cost ($/kWh)	Triangular(1900,2000,2100)
Constant O&M Cost – no fuel ($/kWh)	Flat(100, 120)
Variable O&M Cost ($/kWh)	Flat(0.15,0 .25)
Fuel Cost ($/GJ)	Five-Point (0.45,0.475,0.5,0.525,0.55)
Plant Efficiency	Flat(0.32,0.34)
Load Factor (Capacity Factor)	Triangular(0.6,0.7,0.8)
Years of Loan Repayment	Flat (15, 20)
Discount Rate	Flat (5%, 8%)
Average Interest Rate for Loan Repayment	Flat (5.5%, 7.5%)
Average Annual Rate of Fuel Price Increase	Flat (0.8%, 1%)

Figure 3: Probability Distributions used by Feretic and Tomsic (Feretic & Tomsic, 2005)

Although the price of electricity in a deregulated market makes up a large portion of the uncertainty associated with the cost of nuclear power, it is not the only source. In order to get a comprehensive cost estimate, it is critical to consider other sources of uncertainty and whether their inclusion in the estimation will add quality to the analysis. The use of stochastic and probability models both offer methods of accounting for these uncertainties.

3. Limitations

As the nuclear industry ages, it is becoming increasingly important to have an accurate system for calculating the long-term costs of nuclear power. With each plant that approaches its licensed lifetime, decision makers are required to examine the economic feasibility of extending the plant's license or building a new plant to replace it and letting the current plant continue down its original path toward decommissioning. Each of these alternatives require detailed cost estimations. The current methodologies used for this analysis focus on the uncertainty associated with a deregulated electricity market. The importance of the electricity market risks should not be overlooked, but it must not overshadow other aspects of the model. With that in mind, it is necessary to examine the limitations of the current methodologies, especially those aspects of evaluation that are eclipsed by the focus placed on accurately modeling the deregulated electricity markets of Japan, Europe, and the United States.

One component of cost evaluation that is often overshadowed by market risk is the uncertainty arising from other aspects of construction and operation. Although the current literature addresses uncertainty in variable and capital costs, the effort afforded to modeling theses aspects of nuclear power plant costs is marginal. Additionally little notice is given to uncertainty associated with the time needed for construction. Since construction costs make up a large portion of the total lifetime cost of nuclear power and extended construction forces delays in plant operation, it is critical to consider the risk of cost and time overruns. Any uncertainty about the total construction costs or timelines has the potential to negatively affect investment decisions and deter potential investors.

In addition to overlooking the importance of uncertainty in construction costs, much of the current literature assumes that variable costs are constant. The assumption is based on the premise that the effect of uncertainty on variable costs is small compared to the effect of fluctuations in electricity prices (Takashima, Naito, Kimura, & Madarame, 2007). Although this premise is true, it does not imply that uncertainty in variable costs is not worth consideration in cost estimation models. Additionally, the fact that market uncertainty has a large impact on economic valuations should not lead to the discounting of other sources of uncertainty, especially when performing an in depth analysis of lifetime costs.

Another limitation of current methodologies is that few authors consider the option of abortion. Once licensing is completed, nuclear power plants have the option of continuing with the project or abandoning it. They also have the option of aborting a project that is proving to be a problem. Considering the option of abortion in nuclear power plant valuation, especially when analyzing the prospect of building a new plant, could increase the value of the project. Current methodologies consider investment in a new plant as a real option, but few consider the option to abort a project that has already been started. Part of the reluctance to consider terminating a project stems from the high capital costs associated with nuclear power plants, but the ability to terminate a project offers management the flexibility to control the amount of 'good money thrown after bad.' By considering the option to abort in the analysis, management will be better able to see the value of flexibility.

With the average age of nuclear power plants in the United States hovering around thirty, it is critical to consider the effect aging has on the lifetime costs of nuclear power. There are a number of ways in which aging could impact the cost of a nuclear power plant. First of all an aging plant may require additional safety measures. These measures may include increased regulatory scrutiny to ensure adequate plant safety margins are maintained as the plant ages and could manifest themselves as increases in plant operating or capital cost to address these regulatory concerns. Additionally, an increased probability of equipment failure is often associated with an aging plant. With the amplified concern about equipment failure comes an upsurge in equipment inspections. These inspections in turn cause increased cost. In addition to an increase in inspections there is an increased possibility of maintenance and equipment replacement (Jykama, Pandey, & Hess, 2010). Aging equipment not only increases the need for added safety and maintenance, but it also may affect the amount of electricity produced. The methods currently used in the literature either assume a constant capacity factor throughout the lifetime of the plant or, in the case of Rothwell's analysis in "A Real Options Approach to Evaluating New Nuclear Power Plants," an increasing capacity factor over a plants lifetime. Rothwell based his assumption on increases in plant capacity factors through the 1980's and 1990's (Rothwell, 2006). The recorded capacity increases were the result of new technology and management techniques and have culminated in average nuclear power plant capacity factors in the U.S. exceeding 90%. Since this current level of performance is very high (and near its practical limit), such increases as those seen at the end of the twentieth century are very unlikely to continue in the future. Thus, it will be necessary for data to be analyzed to determine the effect a plants age may have on capacity factors.

With the nuclear industry facing a number of tough decisions about its future direction, it is imperative for economic analysis to be efficient and effective. The lack of consistency in the methods currently being used for economic analysis make the goal of effective analysis difficult to achieve. There is no standard practice used in the economic analysis of nuclear power plants. As a result there is a wide range of methods employed and an even wider range of cost estimates achieved. Throughout the history of nuclear power plants it has been a common occurrence for costs to be under estimated due to uncertainties such as price and interest-rate uncertainty and nuclear specific uncertainties such as those associated with the regulatory process and obtaining public approval of the project. Additionally, there is a history of wide ranging estimates that can vary a great deal. A table displaying the cost of nuclear power in cents per kilowatt hour for four reports discussed in a study conducted by ABS Energy can be found in Figure 4. The ABS Energy Study, which examined the economics of nuclear power by reviewing several reports, found that the highest reported cost estimate of nuclear power generation was approximately 50% greater than the lowest (ABS Energy Research, 2009). The discrepancies in cost estimation make it difficult for investors to get a clear picture of the costs and benefits of investing in nuclear power. With all of the contradictory information available, it is difficult to determine which analysis is the most accurate. For cost analysis to be an effective decision making tool, it will be necessary for the cause of incongruities in cost estimates to be examined and changes to be made.

Report Source	US ¢/kWh
MIT	6.7
Royal Academy of Engineering	4.5
Nuclear Energy Association	4.6
University of Chicago	6.2
Scully	4.6

Figure 4: Cost of Nuclear Generation with 40 Year Life and 85% Capacity Factor (ABS Energy Research, 2009)

4. Recommendations

The majority of the current literature addresses the issue of economic analysis of nuclear power plants in a haphazard way, usually focusing on a single aspect of the model and making simplifying assumptions about the rest. This method has lead to advances in methods for dealing with the time value of money and market uncertainty, but it has neglected the importance of an in depth examination of cost and revenue factors and plant policies that could affect them. Nuclear power plants are complex systems with many facets that need to be considered. In order to accurately estimate the lifetime costs of nuclear power plants, it is necessary to approach economic analysis from a systems perspective. A systems approach will help analysts understand the system as a whole and incorporate the many components of the plant into their model (Sireli & Mengers, 2009). The first step towards a systems approach is ensuring that the modeling effort draws on knowledge from a variety of experts, engineers, and departments. It should also consider a number of costs, revenues, uncertainties, and risks for inclusion into the model. By using a systems approach to economic analysis, the decision makers will get a more accurate and holistic view of their alternatives.

By approaching the analysis from a systems perspective, many of the factors that are overlooked in current methodologies will be considered. One such factor is the effect of aging on equipment failure, capacity factors, and costs. The aging of nuclear power plant structures and systems can affect safety and cost factors. Little research has been done on the effects of aging on the lifetime cost of nuclear power plants, but research has been done on the effects of aging on plant generation and safety. Specifically research has been done on incorporating equipment aging models into generation risk assessment and probabilistic safety assessment (Jykama, Pandey, & Hess, 2010) (Kancev & Cepin, 2011). In "Evaluation of Risk and Cost using an Age-dependent Unavailability Modeling of Test and Maintenance for Standby Components," Kancev and Cepin consider linear and Weibull component aging models. For these models the failure rate of the component is modeled as a function of time. Components are defined as "the smallest part of the system, an entity which is not further subdivided and is both necessary and sufficient to be considered for analysis." The equations for the failure rate are given below:

$$\lambda_{lin}(t) = \lambda_0 + \theta_1 t \tag{9}$$

$$\lambda_{Weib}(t) = \theta_2 t^{\theta_3} \tag{10}$$

where $\theta_1, \theta_2, \theta_3$ are aging rate coefficients. These models were then incorporated into a fault tree analysis and subsequent cost functions (Kancev & Cepin, 2011). A similar method was suggested for incorporation into generation risk analysis by Jyrkama *et al* in "Integration of Degradation Models into Generation Risk Assessment: Challenges and Modeling Approaches." In their work they incorporate degradation predictions into the existing GRA framework by making fault tree analysis time-dependent (Jykama, Pandey, & Hess, 2010). Both of these methods can be used as a starting point for the incorporation of aging into economic models. By extending these models to incorporate the degradation or aging models of all of the critical components, the effect of aging on the entire nuclear system could be captured. Although extending current methodologies provides a direction for possible exploration, these extensions are no easy feat to accomplish. There are two significant hurdles that must be cleared before these model extensions can be applied. First of all, incorporating the aging model of an array of components will have an impact on computational complexity, which could significantly increase the computational time required to generate a solution. Secondly, many components do not yet have accurate degradation models and the degradation models that exist are plagued with uncertainty. In order for the extensions of the models presented by Kancev and Cepin and Jyrkama *et al* to be applicable, these two issues must be addressed. In addition to the methods discussed above, it would be beneficial to look into aging models of the entire nuclear power plant. If a model that could capture the effects of aging on the entire plant could be developed and validated, it could reduce the amount of data and computation needed to capture the effects of aging on the lifetime cost of nuclear power plants.

Another factor affected by aging is the probability of plant failure. In light of recent events it is more important than ever to consider the possibility of a disaster and the costs associated with it. Although the probability of an event like Chernobyl or the recent catastrophic earthquake in Japan that precipitated the accident at the Fukushima Dai-ichi plant occurring is small, the consequences, costs, and liabilities to the plant owners due to these types of events are enormous. As such, it is important for these risks to be included in any analysis of plant life cycle costs. Accidents, however, are one of the most challenging components to analysis and there is no general consensus on how to calculate their economic impact. Additionally, they require input from Probabilistic Safety Assessment and frequently rely on simplifying assumptions (Kessides, 2010). Despite these difficulties, new research on how to best incorporate estimates of the consequences and costs of nuclear disasters into a coherent decision making framework could bring an added layer of accuracy and integration to both economic and safety analysis.

In addition to incorporating aging models into economic analysis, it is critical for analysts to find ways to more accurately calculate the time and cost of construction. According to Pindyck, developers face two types of uncertainty during the construction phase of nuclear projects. These two types of uncertainty are technical uncertainty, which refers to the time, material and resources required to complete the project, and input cost uncertainty (Pindyck, 1993). Technical uncertainty can be mitigated by proper management and exercising the option to abandon the project in the face of increasing time and resource requirements (Holt, Sotkiewicz, & Berg, 2010). Input cost uncertainty on the other hand is pervasive throughout the entire construction period and cannot be mitigated by beginning development and gathering new information. Rather, it can be mitigated by delaying development until more is known about regulation and material costs (Holt, Sotkiewicz, & Berg, 2010). There are a number of ways to deal with these two uncertainties. The most straight forward way of dealing with input cost uncertainty, is to handle it in the same manner as electricity price uncertainty is handled. In most cases this means using a stochastic model, such as GBM, to represent the input costs. The technical uncertainty is more difficult to handle, but according to Pindyck this type of uncertainty is less critical than the uncertainty associated with input costs. Pindyck however did account for both input cost and technical uncertainty in his model, which is given in detail in Appendix B: Pindyck's Model for Nuclear Power Plant Construction.

Pindyck's model is one of the few models I found that addressed the uncertainty inherent in construction costs and timelines in a rigorous manner. Additionally, the similarities between the method Pindyck uses to account for construction uncertainty and those used to deal with uncertainty in electricity prices make it easy to integrate the model into current economic analysis. Although Pindyck's model provides one option for dealing with construction uncertainty, research into other possible methods of accounting for uncertainty should be performed. Pindyck's model was developed prior to the time when deregulation of electricity markets came into vogue and as such does not deal with uncertainty beyond that experienced during construction. Regardless of its flaws, Pindyck's model is a good first step in incorporating construction uncertainty into economic models.

It will also be beneficial for more analysts to consider including the option to abort a project in economic models. By incorporating management flexibility into the analysis, the decision makers get a more accurate understanding of the projects value. Additionally, considering the option to abort a project helps to mitigate the technical uncertainty encountered during the construction and development phase of the project (Holt, Sotkiewicz, & Berg, 2010). There are a number of opportunities for management to cut their losses and cancel the project. The most obvious of these opportunities occurs during the time between completing the licensing process and beginning construction or renovations. During this period decision makers are able to get more accurate information about the cost of construction or equipment upgrades. With this additional information, management can get a better estimate of the project's value and decide to continue with the project or abort it. The opportunity to abort at this stage of the project is particularly beneficial because the project can be cancelled with limited financial loss. In “Valuation and Optionality of Large Energy Industry Capital Investments,” Graber and Rothwell consider two options: the option to pursue licensing and the option to begin construction. By including both options, the option to abort between the licensing decision and the start of construction is inherent in their model (Graber & Rothwell, 2006). Pindyck also included the option to abort a project in his 1993 paper on construction uncertainty (Pindyck, 1993). By including the option to abort in their models, theses authors have given decision makers a more accurate view of the lifetime costs and reinforced managements’ power to abort a failing project.

Finally, as Kessides says in “Nuclear Power: Understanding the Economic Risks and Uncertainties,” it is “imperative to develop a uniform set of cost-engineering standards” for nuclear power plant costing (Kessides, 2010). The goal of lifetime cost assessment is to aid decision makers in determining the fate of nuclear power plant projects. Under the current system of cost estimation, this goal is not being achieved. The data currently available on lifetime costs vary a great deal from plant to plant, making it difficult to determine which data are accurate and reliable. Additionally, the wide range of estimated lifetime costs make it difficult for investors and policy makers to rely on lifetime cost measures as a useful decision support tool. Although addressing this issue and creating a standard method for cost estimation seems daunting, it is not impossible. The nuclear industry already has standard methods of assessing safety risks in the form of Probabilistic Safety Assessment (PSA). In fact, the International Atomic

Energy Agency has defined PSA as “the appropriate application of Probabilistic Risk Assessment (PRA) to safety decisions (Hayns, 1999).” The success of PSA as the premier method of calculating safety risks stem from its transparency and flexibility. In order to create an equivalent method for the economic analysis of nuclear power plants it will be necessary to perform a detailed meta-analysis of the methodologies currently in use and draw from them the important details and concepts for a transparent and effective economic model. It will also require the financial and political support of at least one of the large nuclear organizations, such as the IAEA.

Once established, the set of cost-engineering standards will benefit the nuclear industry in a variety of ways. First of all, the development of uniform standards for cost-engineering will enable the effective and efficient comparison of plant costs across and within nations. Secondly, uniform standards would allow researchers to shift their focus from model creation to model advancement, which in turn would lead to a more accurate standard model. Uniform standards will also give investors the ability to easily compare the economic viability of different projects and make more economically sound decisions. Finally, establishing these standards would force companies to provide more detailed examinations of cost estimates and the assumptions underlying them. As these estimates become available to the public, companies will be forced to take a hard look at how their expenses compare with other companies’ and explore methods of cutting costs and remaining competitive. Although the establishment of universal costing standards would require a great deal of effort and coordination, the benefits to be gained justify the costs.

5. Conclusions

As more and more nuclear power plants approach the end of their planned lifetimes, decision makers are becoming increasingly interested in the economic viability of lifetime extensions and the construction of new plants. In order to adequately assess these two alternatives, there must be a solid analytical framework for lifetime cost estimation. The methodologies currently in use are not capable of serving as that framework. They are, however, an excellent foundation upon which that framework can be built. Researchers should explore techniques that can be used to strengthen and build upon the foundation created by current methodologies. Specifically, researchers can search for the best ways to incorporate aging and degradation models, accident risk models, and the option to abort into the current methodologies. Additionally by examining the current methodologies researchers will be able to ascertain which methodologies are the most effective and use these as a basis for a standard lifetime cost model.

The recommendations proposed in this paper suggest building upon current methodologies to create more accurate models of the lifetime cost of nuclear power plants. Additionally the recommendations call for a standard systems approach to economic analysis. Incorporating the recommendations into the current modeling framework will propel economic analysis to a higher level and open the door for a frank discussion of nuclear power plant costs and the discrepancies inherent in current analysis. The limitations of the current methodologies act as a barrier to sound decision making. Creating a standard lifetime costing model that considers a range of diverse events and costs will give investors a tool for comparing the economic viability of different projects and for making judicious decisions in the future.

Appendix A: Uranium Prices

The monthly spot prices of uranium futures from 2007 to the present, as well as the price of uranium are depicted in Figure 5 and the logarithmic return of the uranium prices and spot prices are depicted in Figure 6. The graphs were created using data from Cameco Corp, one of the world's largest uranium producers (Cameco Corp, 2011).

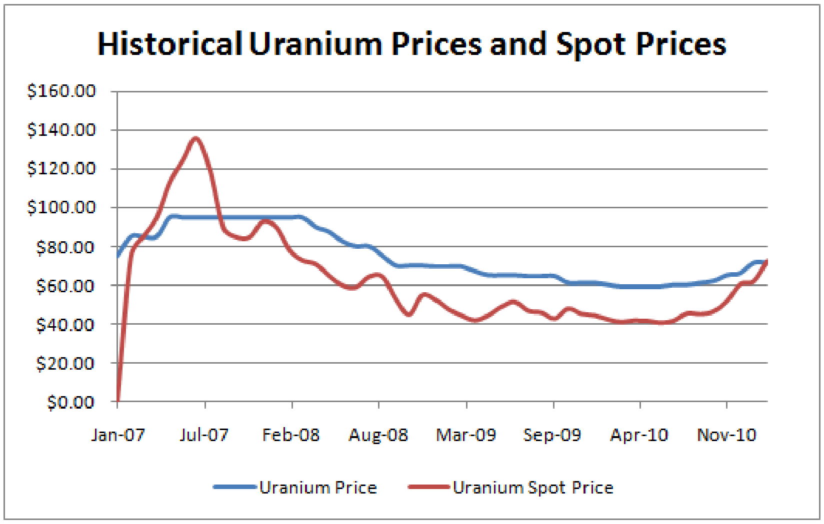

Figure 5: Uranium Prices and Spot Prices (Cameco Corp, 2011)

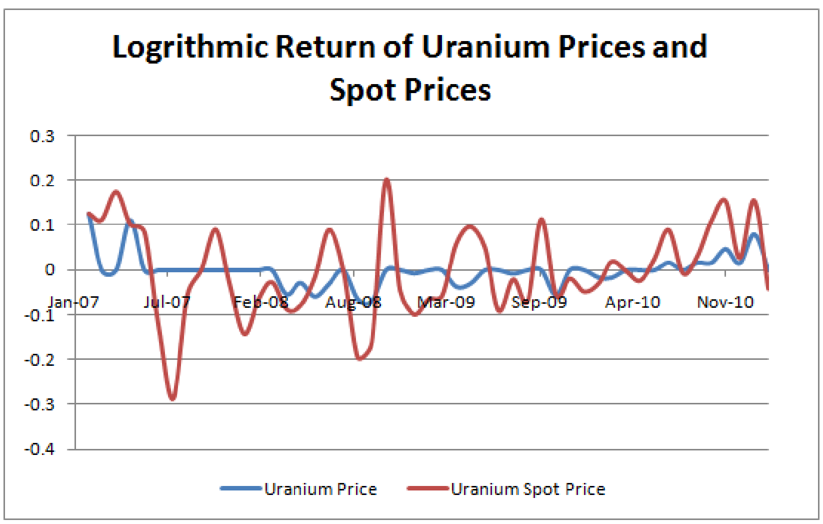

Figure 6: Logarithmic Return of Uranium Prices and Spot Prices (Cameco Corp, 2011)

Appendix B: Pindyck's Model for Nuclear Power Plant Construction Costs

Let the expected cost to completion be represented by $K(t)$ and let $K(t)$ follow a controlled diffusion process, which is given below:

$$dK = -Idt + g(I, K)dz \tag{11}$$

where

I: The rate of investment.

$z(t)$: Wiener Process.

Equation (12) allows the expected cost to completion to change stochastically and ensures that the remaining project cost decreases with ongoing investment.

Now assume that there is a maximum rate of investment,k and let $F(K) = F(K; V, k)$ be the value of the investment opportunity. Then $F(K)$ satisfies the following equation:

$$F(K) = \max_{I(t)} E\left[Ve^{-\mu\overline{T}} - \int_0^{\overline{T}} I(t)e^{-\mu t}dt\right] \tag{12}$$

subject to Equation (11), $0 \leq I(t) \leq k$, and $K(\overline{T}) = 0$. Here μ is the risk-adjusted discount rated and $\overline{T}$, the time of completion, is stochastic.

In order for Equation (11) to make sense economically, we would like the following properties to hold:

i) $F(K; V, k)$ is homogenous of degree one in K, V, and k.

ii) $F'_K < 0$ or an increase in the expected cost of an investment should always reduce its value.

iii) The instantaneous variance of dK is bounded for all finite K and approaches 0 as K approaches 0.

iv) If the firm invests at the maximum rate k until the project is complete, $E\left[\int_0^{\bar{\bar{T}}} kdt = K\right]$.

By setting $g(I, K) = \beta K\left(\frac{I}{K}\right)^{\alpha}$, with $0 \leq \alpha \leq \frac{1}{2}$, the above conditions are satisfied. Since we are only concerned with two types of uncertainty we can restrict our analysis to $\alpha = 0$ and $\alpha = \frac{1}{2}$, which correspond to input cost and technical uncertainty respectively.

These two cases can then be combined into a single equation to represent the evolution of K over time:

$$dK = -Idt + \beta K\left(\frac{I}{K}\right)^{1/2} dz + \gamma K\left(\frac{I}{K}\right)^{0} dw = -Idt + \beta(IK)^{1/2}dz + \gamma Kdw \tag{13}$$

where dz and dw represent two uncorrelated Wiener processes.

Since the Wiener process representing input cost uncertainty, dw, could be correlated with the market, we cannot use the risk free rate for μ. By assuming that dw, is spanned by existing assets in the economy, i.e., if in principle one could replicate movements in dw with some other asset or dynamic portfolio of assets, we can eliminate μ. Now let x be the price of an asset or dynamic portfolio of assets perfectly correlated with w, so that dx follows:

$$dx = \alpha_x x dt + \sigma_x x dw \tag{14}$$

By the Capital Asset Pricing Model (CAPM), the risk-adjusted return on x is $r_x = r + \theta\rho_{xm}\sigma_x$, where r is the risk free rate, θ is the market price of risk, and ρ_{xm} is the instantaneous correlation of x with the market portfolio.

It can be shown that $F(K)$ must satisfy the Bellman equation for the stochastic dynamic program given by Equation 15. The Bellman equation is given below:

$$\frac{1}{2}\beta^2 IKF'_{KK} - IF'_K - \varphi\gamma KF'_K - I = rF \tag{15}$$

where $\varphi = (r_x - r)/\sigma_x$. Recall that $r_x = r + \theta\rho_{xm}\sigma_x$, thus $\varphi = \theta\rho_{xm}$. Since θ, is an economy wide parameter, the only project specific parameter needed to determine φ is ρ_{xm}, which is just the correlation coefficient between fluctuations in input cost and the stock market. Since Equation 15 is linear in I, the rate of investment that maximizes $F(K)$ is always equal to either 0 or k. Thus there exists a point K^*, such that $I(t) = k$ when $K \leq K^*$ and $I(t) = 0$ otherwise.

Finally, we can determine the value of K^* and $F(K)$ by solving Equation 15 with the following boundary conditions:

i) $F(0) = V$

ii) $\lim_{K\to\infty} F(K) = 0$

iii) $\frac{1}{2}\beta^2 K^* F'_{KK}(K^*) - F'_K(K^*) - 1 = 0$

iv) $F(K)$ is continuous at K^*.

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